

VALIDATION OF A MODULATED FORCE EMS SYSTEM FOR FINAL SOLIDIFICATION ZONE STIRRING

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ABSTRACT. Experimental and computational validation of a dual stator EMS system designed to produce low frequency modulation of the Lorentz force is provided. Experiments were conducted to measure the average angular velocity in a stirred mercury column. Subsequently, the structure of cast A357 aluminum alloy, subjected to modulated and unmodulated EMS while solidifying, was examined. The flow produced in both configurations was also estimated by a computational flow model in an effort to correlate observed improvements to flow characteristics produced by the modulated forces.

INTRODUCTION

In-mold Electromagnetic Stirring (M-EMS) is widely used when continuously casting steel billets, blooms and slabs. For billets and blooms, M-EMS is most often accomplished using a rotating magnetic field that induces electric current to flow within the molten pool being cast. The resulting electromagnetic (Lorentz) forces cause the molten metal to rotate, much as the rotor of an induction motor rotates under the action of similar forces. Due to the presence of the copper casting/cooling mold, the source electromagnetic fields must, of necessity, be of low frequency (typically 3 to 8 Hz). The low frequency limits the magnitude of the induced currents, and thus of the forces, that produce rotary motion.

There is equally strong interest in using EMS to stir far below the mold in the final solidification zone of a continuous casting strand. Regrettably, conventional EMS systems have proven to be somewhat ineffective when applied in this region. As a potential solution, there recently has been considerable interest in applying modulated Lorentz forces in an effort to develop a broadly distributed vigorous stirring in the final zone [1-3].

Several of the proposed modulation schemes rely on special power supplies that produce source currents having a prescribed harmonic content [1]. This may not be a practical solution at high power. An alternative is to use multiple, but conventionally designed, stators and power supplies [2]. With the latter scheme, very low frequency modulation of the Lorentz force in the inter-stator region(s) is achieved by having at least two stators operate at slightly different frequencies. By operating the individual stators at high frequency (up to approximately 60 Hz), large amplitude induced currents and forces can be achieved.

It was proposed in [3] that certain flow performance aspects of the modulated system could be usefully predicted by employing an Unsteady Reynolds Averaged Navier Stokes (U-RANS) modeling approach. U-RANS is useful when the time varying aspects of the turbulent flow are substantially separated from the time scale of the modulated forces. Recently

published measured data by Fautrelle et al [4] suggests that this might indeed be the case provided the frequency differential between two adjacent stators was less than approximately 0.5 Hz. Using a U-RANS model, typical performance characteristics for the proposed final solidification stage EMS system were obtained. The predicted results indicated that the small radius molten zone could be effectively stirred. More important, despite the fact that the modulated forces themselves were confined to a relatively small zone at the system mid-plane, the modulation of the stirring velocities extended to the extremities of the two stators.

The purpose of the present paper is to experimentally and computationally validate the principle that low frequency modulation of the stirring forces, in the final solidification zone, can improve the quality of the solidified product. In order to do so, two sets of experimental trials were conducted. In the first, angular velocities were measured in a mercury column being stirred by a system similar to the one described in [3]. The net magnetic field and the angular velocity were measured as a function of axial position and excitation (current magnitude and frequency). Large and small frequency differentials were considered. The second trial measured the impact that various stirring strategies had on the quality of the cast product. Rather than steel, an aluminum alloy (A357) was chosen for the solidification study since equipment to melt the lower melting point aluminum was readily available. The molten aluminum was delivered to a casting mold and it was stirred during the solidification cycle. The solidified product was then sectioned and examined in terms of globule mean area, mean length and density.

Both trials are described in this paper and particular attention is given to a comparison between the experimental results that were obtained and the velocity distributions that were predicted by the URANS flow model.

EXPERIMENTAL VALIDATION TRAILS

Angular Velocity Measurements in Mercury Column

A modulated force EMS system, containing the essential features of the approach proposed in [2,3] for final zone stirring, is illustrated in Fig. 1a. This system contains two identical 3-phase salient pole stators, each of which produces a rotating magnetic field. As this system is to be used in the final solidification zone, it does not incorporate a copper mold and thus can operate at frequencies up to line frequency. When the two stators are excited at different angular frequencies, for example f_U and f_L , the effective Lorentz force developed in the inter-pole region has a low frequency component in addition to the two time average contributions:

$$F_i(\vec{r}, t) = F_{DC,U,i}(\vec{r}) + F_{DC,L,i}(\vec{r}) + F_{MOD,i}(\vec{r}, t) \cos [(f_U - f_L)t + \Phi_{MOD,i}(\vec{r}, t)] \quad (1)$$

Here, $i = x, y, z$. Due to inertia, the modulated force only impacts the molten metal when the frequency difference is small. The Lorentz force also contains double frequency and $(f_U + f_L)$ terms, but the fluid is generally unable to respond to such forces. It will also be noted that in Fig. 1a, there is a reasonable separation between the upper and lower sets of coils.

An industrial scale version of the final zone stirrer is shown in Fig. 1b where a square cross section stainless steel container, filled with mercury, has been positioned inside the assembly. The dimensions of the mercury column were 110 x 110 x 1000 mm. A vane-type velocity probe was attached to the lower end of a graphite shaft, the upper end of which was fixed inside a frictionless air bearing. The axial position of the probe plus air bearing assembly could be adjusted relative to the meniscus of the mercury column. The rotation of the velocity probe was measured by a tachometer and recorded by a data acquisition system. The probe system was used to measure angular velocity as a function of axial position.

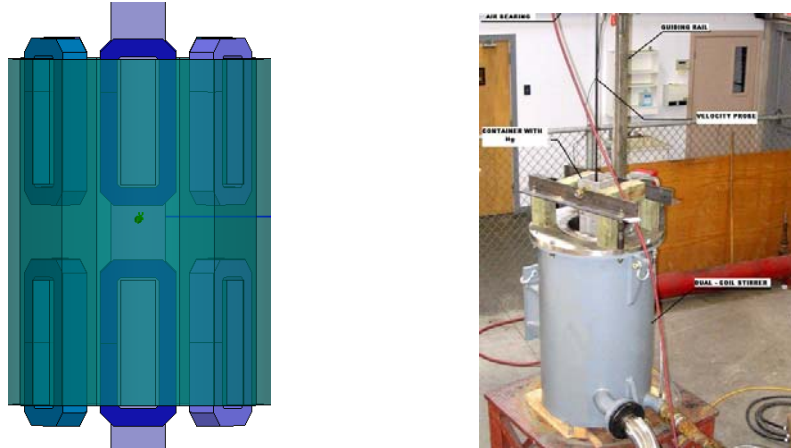


Figure 1a (left). Two stator EMS system for final solidification zone modulated stirring.
Figure 1b (right). Industrial prototype used for measurement of flow in mercury column.

For the purpose of the mercury trials, the upper stator was supplied at 18 Hz, with a rated coil current of 200 A rms. The lower stator was also rated at 200 A rms, and was supplied at frequencies of 17.0, 17.50, 17.75, and 18.0 Hz, with the phase sequence such that the rotating field could either assist or oppose that of the upper stator. The mercury trials, including detailed results, are more fully described elsewhere [5].

Typical axial distributions of angular velocity are shown in Fig. 2. The angular velocities have been time averaged. It will be noted that the use of different frequency magnetic fields, in assist mode (Case b), slightly reduces the angular velocity that is produced. When the same frequencies are used, but in opposing or brake mode (Case C), there is a significant reduction in the magnitude of the angular velocity. Note that these measurements do not show instantaneous modulation effects.

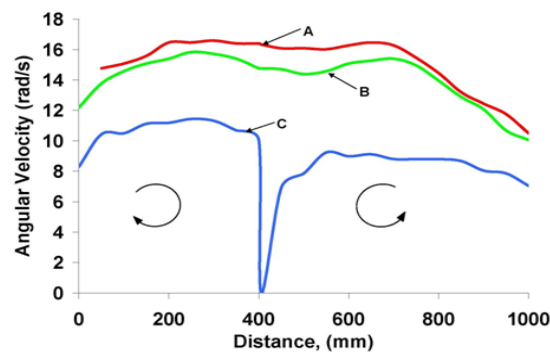


Figure 2. Angular velocity profiles in a column of mercury as function of stirring mode.
A. Common rotational direction magnetic fields, both of frequency 18.0 Hz.
B. Common rotational direction fields of frequency 18.0 Hz (Upper), 17.5 Hz (Lower).
C. Opposing rotational direction fields of frequency 18.0 Hz (Upper), 17.5 Hz (Lower).

Solidification Studies with Cast Aluminum Alloy A357

A second set of trials were undertaken in which modulated and un-modulated rotating magnetic fields were applied to aluminum alloy A357 as it solidified. As illustrated in Fig. 3, the alloy was melted in a conventional induction furnace, and then transferred via a fused silica launder to an air-cooled stainless steel mold arranged inside a two stator stirrer. The stirrer for these tests was of a type that is conventionally used for in-mold stirring. As with

the mercury trials, tests were conducted for a range of operating conditions, modulated and un-modulated, unidirectional rotation and counter rotation, as summarized in Table 1. A full description of these trials can be found elsewhere [6].

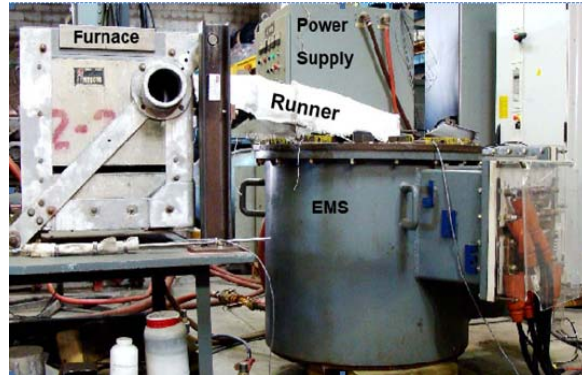


Figure 3. Experimental set-up used for stirring A357 Aluminum alloy.

Table 1. Stirring settings used for A357 casting trials

Cast No.	Electric Current and Frequency		Applied Stirring Method
	Upper Stirrer	Lower Stirrer	
1	No stirring		
2	0	140A, 11Hz	Unidirectional un-modulated
3	160A, 8Hz	140A, 11Hz	Counter-rotating modulated
4	150A, 10.5 Hz	140A, 11Hz	Counter-rotating modulated
5	160A, 10 Hz	140A, 10Hz	Counter-rotating un-modulated
6	160A, 8 Hz	140A, 11Hz	Unidirectional modulated
7	150A, 10.5 Hz	140A, 11Hz	Unidirectional modulated

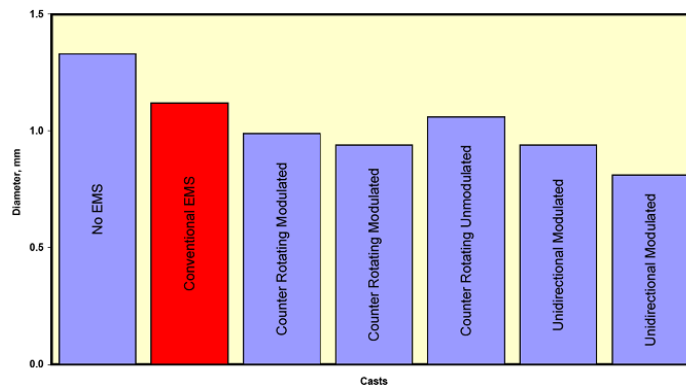


Figure 4. Average grain diameter in A357 macrostructure as function of stirring method.

Representative results taken from the solidification trials are shown in Fig. 4 which shows the average grain diameter of the cast product for various stirring strategies. Conventional

EMS, using a single stator (Cast 2 - Table 1), is taken as a benchmark. As Fig. 4 illustrates, Cast 7, involving 0.5 Hz modulation, results in the greatest reduction in terms of average grain diameter. The improvement offered by modulated unidirectional stirring was evident in all of the structural metrics that were considered in the trial [7].

COMPUTATIONAL EMS MODEL

Electromagnetic modeling

In parallel with the mercury and aluminum trials, computational modeling of the expected fluid flow was undertaken using a previously developed coupled EMS model [3]. In this model, the Lorentz forces were estimated by first assuming that the $\mathbf{u} \times \mathbf{B}$ coupling between the electromagnetic and the flow fields could be neglected. Considering the model shown in Fig. 1a, the distributions of magnetic flux density $\mathbf{B}$ and current density $\mathbf{J}$ were obtained separately for each stator, *acting alone*, at their respective frequencies f_U and f_L . Any available 3D eddy current software can be used for this purpose. Knowing the individual components of $\mathbf{B}_U$, $\mathbf{B}_L$, $\mathbf{J}_U$ and $\mathbf{J}_L$, the magnitude of each term in (1), together with the phase of the modulation force term, can be constructed at a post processing stage. For the work reported in this paper, the force determination was actually done within the fluid flow software.

Turbulent flow modeling

Fluid flow modeling used ANSYS Fluent was done by transiently solving a Reynolds Averaged version of the momentum equation:

$$\rho \frac{\partial \vec{u}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} \vec{u}) = -\vec{\nabla} p + \mu \nabla^2 \vec{u} + \vec{\nabla} \cdot \vec{\tau}^{(t)} + \vec{f}_b \quad (2)$$

In (2), $\vec{u}$ is the Reynolds averaged vector velocity, μ is viscosity, p is pressure, $\vec{\tau}^{(t)}$ represents stress due to turbulence and $\vec{f}_b$ is the Lorentz body force given by (1), corrected for $\mathbf{u} \times \mathbf{B}$ effects. As noted in [3], a very simple but approximate space dependent velocity correction factor is given by:

$$K = 1 - \Omega(\vec{r}) / 2\pi f \quad (3)$$

where Ω is the angular velocity at the spatial coordinate $\vec{r}$ and f is either f_U or f_L , depending on which force component is being corrected. It is noted that the velocity correction becomes relatively small for approximately $f > 15$ Hz.

When considering the continuous casting EMS application, it has been found that the turbulent stress term in (2) is best modeled using a 7 equation Reynolds stress model. In this model, each velocity component is assumed to consist of a Reynolds averaged term $\bar{u}_i$ and a fluctuating component u'_i that is representative of local turbulence. During the temporal averaging process, terms of the form $\overline{u'_i u'_j}$ arise which contribute to the Reynolds stresses $\overline{\rho u'_i u'_j}$. Each of the 5 such terms, together with the turbulence kinetic energy k and turbulence dissipation rate ϵ , are assumed to satisfy a transport equation of the general form:

$$\frac{\partial(\rho\Psi)}{\partial t} + \vec{\nabla} \cdot (\rho \vec{u} \Psi) = C_\Psi \vec{\nabla} \cdot \Gamma_\Psi \vec{\nabla} \Psi + G_\Psi - S_\Psi \quad (4)$$

where Ψ is the quantity of interest, Γ is a material constant, C is a general constant, while G and S are source and sink terms, respectively.

The solution methodology when modeling the flow induced by EMS was to initially neglect modulation effects and to run the transient solution for approximately 100 seconds in flow time. This was generally sufficient to iterate to a steady state. The time varying modulation forces, represented by the third term in (1), were then introduced and, again, the solution was run until an sinusoidal "steady state" was achieved. Beyond a certain critical frequency, the modulated flow was in fact identical to the flow that was obtained during the initial steady state. In other words, inertia prevented the fluid from responding to the modulated forces. Below that critical frequency, the flow was characterized by a sinusoidal modulation about a mean.

It is important to note that the time dependent flow predicted by this model is *time averaged*; it is not in any way representative of the temporal velocities that are predicted by spatial averaged methods such as Large Eddy Simulation. Rather, this Unsteady RANS model estimates the response of a temporal average velocity to a very slowly varying driving force.

COMPUTATIONAL VALIDATION STUDIES

Stirring of mercury column

The mercury trials were undertaken using an industrial scale modulated force EMS system, the electromagnetic model of which was shown in Fig. 1a. The actual stirrer was shown in Fig. 1b. The purpose was to confirm that the computational flow model was capable of predicting the measured (average) angular velocities as a function of axial position.

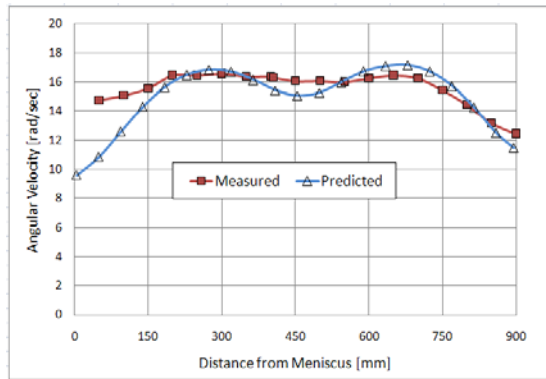


Figure 5. Angular velocity ($r = 45\text{mm}$). 50% rated current. Lower stator @ 18 Hz. Upper stator @ 18 Hz Assist Mode.

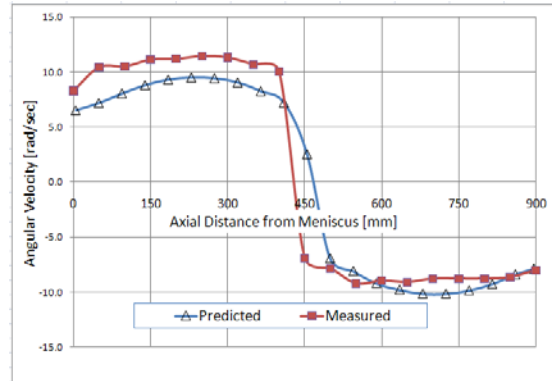


Figure 6. Angular velocity ($r = 45\text{mm}$). 50% rated current. Lower stator @ 17.5 Hz. Upper stator @ 18 Hz Brake Mode.

Fig. 5 compares measured and predicted angular velocities at a radius of 45 mm when both stators in Fig. 1b operate at the same frequency (18Hz) and 50% of rated current. Both magnetic fields rotate in the same direction. The computational model provides an excellent estimate of velocity distribution, except at the free surface. It is emphasized that the measurements were made on an industrial stirrer. It should also be noted that at 18 Hz, the correction for $\mathbf{u} \times \mathbf{B}$ effects is quite small. Fig. 6 shows the comparison when the two magnetic fields are counter rotating and the excitation frequencies differ by 0.5 Hz. Again, the agreement is excellent.

Fig. 7 shows the measured and predicted angular velocities where the upper and lower stators operate in assist mode but at a frequency differential of 0.5 Hz. As can be observed, the flow model underestimates the angular velocity in the inter-stator region by 12-15%. This is nevertheless deemed to be acceptable. Fig. 7 also illustrates that the modulation forces have

a modest effect on the *average* angular velocities for this particular operating condition. It must be emphasized that the flow model being used can only estimate the time variation of *average* velocities. It cannot predict the instantaneous variations, in this case the variation in time of the velocity at a particular point in space. Fig. 8 shows typical measured data for the latter. To estimate instantaneous velocities, higher level models (e.g. LES) would have to be used.

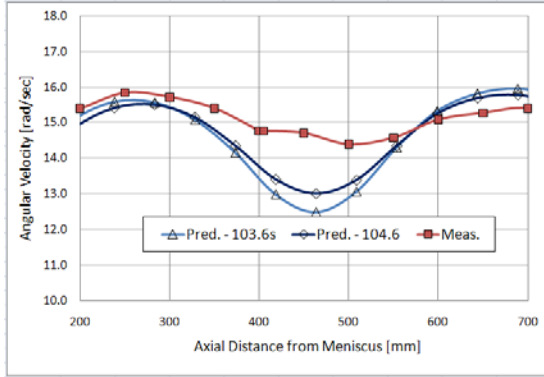


Figure 7. Angular velocity ($r = 45\text{mm}$). 50% rated current. Lower stator @ 17.5 Hz. Upper stator @ 18 Hz Assist Mode.

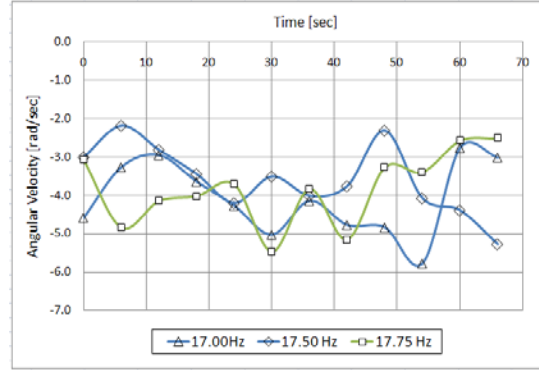


Figure 8. Angular velocity as function of time 460 mm below meniscus. 50% rated current. Upper stator @ 18 Hz. Lower stator counter rotating @ 17, 17.5 and 17.75 Hz.

Solidification Studies with Cast Aluminum Alloy A357

The second set of validation trials consisted of metallographic studies of A357 aluminum alloy cast samples that were subjected to EMS during solidification. The equipment used was illustrated earlier in Fig. 3. This stirrer featured upper and lower stators of unequal dimensions, but with closer spacing than the unit used for the mercury trials.

The trials indicated that, relative to conventional stirring (Case 2 in Table 1), modulated stirring with low frequency differential (Case 4 and Case 7) resulted in a significant improvement in the quality of the cast product. It was not possible to measure actual stirring velocities during the solidification trials. Nevertheless, based on the good agreement that was obtained with the mercury measured data, it was felt that the computational flow model could be used with reasonable confidence to gain insight relative to the A357 results.

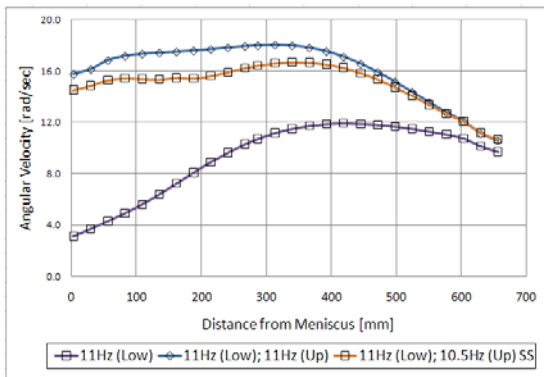


Figure 9. Estimated angular velocities for various cases during A357 casting trials. Single stator, both stators at 11 Hz and 0.5 Hz modulated stirring (Case 7).

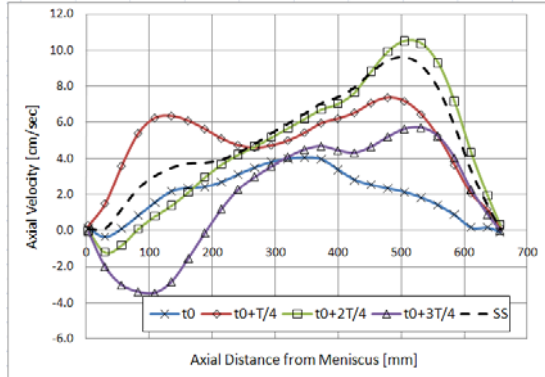


Figure 10. Distribution of axial velocity, averaged on surface of radius 10 mm, for 0.5 Hz modulated stirring (Case 7).

Fig. 9 shows the time averaged angular velocity, during the solidification trials, estimated for the stirrer of Fig. 3 for Case 1 (the Lower stirrer only operating), for Case 7 (both stirrers operating with a differential frequency of 0.5 Hz) and also for a case where both stirrers operate at the same frequency. For the same current, as expected, a more vigorous broadly distributed stirring is obtained when both stators are excited. Equally obvious, this correlates with the improved quality of the cast product. The 0.5 Hz modulated force that acts in Case 7 is of sufficiently low frequency that it impacts the averaged velocities, both tangential (i.e. angular) as well as axial. This modulation will cause the 11 Hz (Low); 10.5 Hz (Up) profile shown in Fig. 9 to oscillate, particularly in the inter-stator region.

The flow model showed that the modulation had a pronounced impact on axial velocity, particularly near the center axis. Representative profiles are shown in Fig. 10; these are circumferentially averaged values, as a function of axial position, on a cylindrical surface of 10 mm radius. It is suggested that this impact of modulated stirring contributed to the observed improvement in solidification structure.

CONCLUSIONS

Experimental and computational trials have been conducted with the objective of quantifying the improvement that modulated EMS provides when applied in the final solidification zone. Experimentally, angular velocities produced in a mercury column by an industrial grade stirrer, specifically designed for final zone stirring, were measured for a range of operating conditions. The measured data were shown to be in good agreement with stirring velocities predicted by a computational flow model. The model included the impact of low frequency modulated stirring forces. Various stirring strategies were then applied when casting A357 aluminum alloy. Metallographic examination of the cast product showed that the greatest quality improvement was obtained when low frequency modulated stirring was used. The computational models indicated low frequency modulated forces were capable of causing marked changes in the axial flow in close proximity to the system center axis. It is suggested that this contributes to the observed quality improvements.

REFERENCES

- [1] Eckert, S., Nikrityuk, P.A., Rabinger, D., Eckert, K., Gerbeth, G. (2007), Efficient melt stirring in using pulse sequences of a rotating magnetic field: Part I. Flow field in a liquid metal column, *Mett. Trans. B*, 38B, 977 – 988.
- [2] Lavers, J.D., Beitelman, L.S., Tallback, G.R., Curran, C.P. (2008), A dual EMS system for stirring liquid metals at an advanced solidification stage, *Proc. MEP Symposium*, Hannover, Germany, Oct. 27-29, 2008, 171 – 176.
- [3] Lavers, J.D., Beitelman, L.S., Curran, C.P. (2009), Computational and experimental modeling of an advanced solidification stage electromagnetic stirring system, *Proc. 6th Int. Conf. on EPM*, Dresden, Germany, Oct. 19-23, 2009, 636 – 639.
- [4] Wang, X., Fautrelle, Y., Etay, J., Moreau, R. (2009), A periodically reversed flow Driven by a modulated travelling field: Part I. Experiments, *Mett. Trans. B*, 40B, 82 – 90.
- [5] Beitelman, L., Lavers, D., Tallbäck, G., Curran, C. (2008), A novel method of electromagnetic stirring of liquid metals at an advanced solidification stage, *The 6th European Conference on Continuous Casting*, Riccione, Italy, June 3-6, 2008.
- [6] Beitelman, L.S., Lavers, D., Tallbäck, G., Curran, C. (2009), A novel FEMS system for continuous casting of steel billets and blooms, *Proceedings of the Association of Iron and Steel Technology Conference (AISTech 2009)*, St. Louis, MO, May 4-7, 2009.